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Spacing-Tunable Multi-Wavelength Fiber Laser Based on Cascaded Four-Wave Mixing in Highly Nonlinear Photonic-Crystal Fiber[1]

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Abstract—A multi-wavelength fiber laser based on the cascaded four-wave mixing in highly-nonlinear photonic-crystal fiber is proposed and investigated. The cascade operation is initiated by two strong pump waves boosted by multi-mode pumping erbium/ytterbium co-doped double-cladding fiber amplification technique. A segment of highly-nonlinear near-zero-dispersion-flattened photonic crystal fiber is employed to induce highly efficient cascaded four-wave mixing. The wavelength spacing can be continuously tunable by stretching the fiber Bragg grating. Experimental results show that multiple wavelengths with a high optical side-mode suppression-ratio of >30 dB are achieved. Furthermore, the proposed multi-wavelength fiber laser exhibits an excellent stability at room temperature.

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1. INTRODUCTION

Fiber laser emitting multiple wavelengths simultaneously have attracted considerable interests because of their potential applications in optical instrument testing, optical signal processing, and fiber sensing [1–6]. Various techniques have been studied for achieving multi-wavelength emission, including erbium-doped fiber (EDF) amplifier [7], semiconductor optical amplifier (SOA) [8, 9], fiber Raman amplifier (FRA) [10], and their hybrid amplification technique. It is well known that multi-wavelength EDF lasers experience cross-saturation between different wavelengths that causes unstable lasing due to the homogeneous gain broadening of EDF at room temperature [3]. It is impractical for SOA-based multi-wavelength fiber lasers because they cannot generate multiple-wavelengths with a high optical side-mode suppression-ratio (SMSR) [8]. Moreover, multiple wavelength lasers based on FRA are also unreasonable because they require several pump lasers of very high power levels [10]. Nonlinear optical frequency conversion is another way to achieve multi-wavelength operation. For example, a new configuration of multi-wavelength fiber laser based on the stimulated Brillouin scattering has been reported [11]. By using the $\chi^{(2)}$- or $\chi^{(3)}$-nonlinear optical susceptibilities in nonlinear materials [12], the multi-wavelength fiber also can be accomplished. In comparing with $\chi^{(2)}$-nonlinear materials, $\chi^{(3)}$-nonlinear materials have a lot of advantages in the optical frequency conversion. Recently, multi-wavelength fiber lasers assisted by four-wave mixing have been achieved [13, 14].

Photonic-crystal fiber (PCF) technology has opened new perspective, since they provide a radical enhancement of nonlinearity by restricting the field in a small fiber core [15]. In addition, PCFs also allow dispersion characteristics to be controlled and tailored by structure engineering [16]. Therefore, PCF with high nonlinearity and controllable dispersion provide the opportunity to remarkably improve the efficiency of nonlinear effects, such as four-wave mixing (FWM) [17–23].

In this paper, a multi-wavelength laser based on the cascaded FWM in highly-nonlinear PCF is proposed. Two strong pump waves boosted by multi-mode pumping erbium/ytterbium co-doped double-cladding fiber amplifier are injected into a piece of highly-nonlinear near-zero-dispersion-flattened PCF, and then highly efficient cascaded FWM occurs. The spacing of generated multiple wavelengths can be continuously tuned by stretching the fiber Bragg grating (FBG). Experimental results show that the proposed fiber laser with multi-wavelengths lasing simultaneously can work stably at room temperature.

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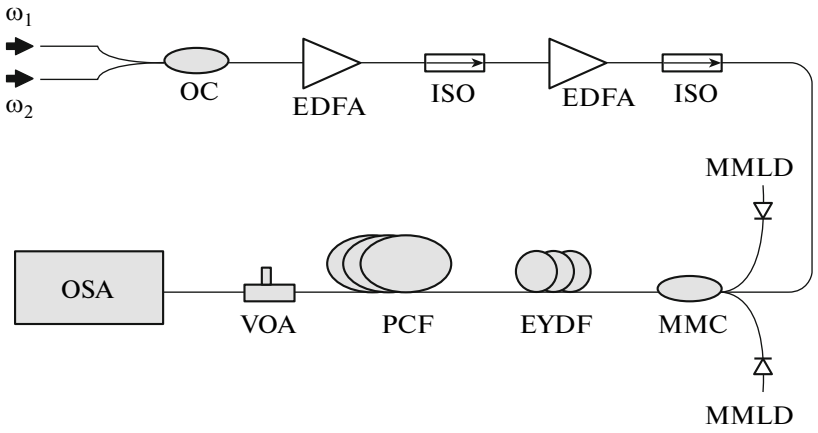

Fig. 1. Schematic diagram for the multi-wavelength laser based on cascaded FWM in PCF. OC: optical coupler, MMLD: multi-mode laser diode, MMC: multi-mode coupler, EYDF: erbium/ytterbium co-doped fiber.

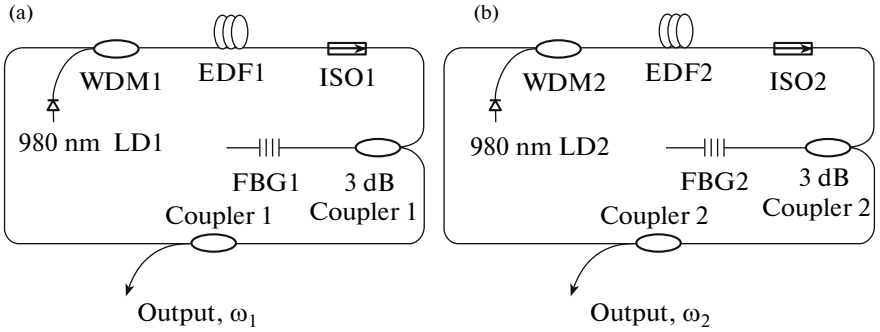

Fig. 2. Configuration of the cavity for pump wave generating. LD: laser diode, WDM: wavelength division multiplexer, EDF: erbium doped fiber, ISO: isolator, FBG: fiber Bragg grating.

2. EXPERIMENTAL SETUP AND PRINCIPLE

The experimental setup is shown in Fig. 1. Two external cavity lasers with continuous-wave lasing (CW), i.e., ω_1 and ω_2, are combined with a 3 dB coupler. Two cascaded erbium-doped fiber amplifiers (EDFAs) are employed as the pre-amplifier. The lasers are amplified mainly by an erbium/ytterbium co-doped double-cladding fiber amplification system. The amplification system consists of a multi-mode laser diode (MMLD) with a tunable power range of $0 - 10$ W, a $(2 + 1) \times 1$ multi-mode coupler (MMC) and a segment of erbium/ytterbium co-doped fiber (EYDF) with double cladding. The $(2 + 1) \times 1$ MMC has a tapered fiber bundle including two segment of standard multi-mode fibers as the pump ports, a segment of standard single-mode fiber as the signal port, and a segment of no-doped fiber with double cladding as the output port. The EYDF has an octagon inner cladding with numerical aperture of ~0.46 and a single mode circle core with numerical aperture of ~0.17. The diameters of the inner and outer cladding are ~130 ± 3 and 245 ± 15 μm, respectively. The outer cladding also serves as the fiber coating. The single-mode core and the proper cladding diameters allow the EYDF to be directly fusion spliced with standard single-mode fiber. A segment of near-zero-dispersion-flattened PCF with the length of 100 m and the nonlinearity coefficient of ~11 W^{-1} K m^{-1} is used for efficient generation of cascaded FWM.

In experiment, the forward pumping configuration is employed to decrease the noise. The signal light pre-

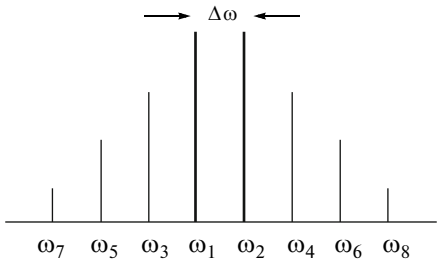

Fig. 3. A sample of cascaded FWM induced by two pump waves ω_1 and ω_2.

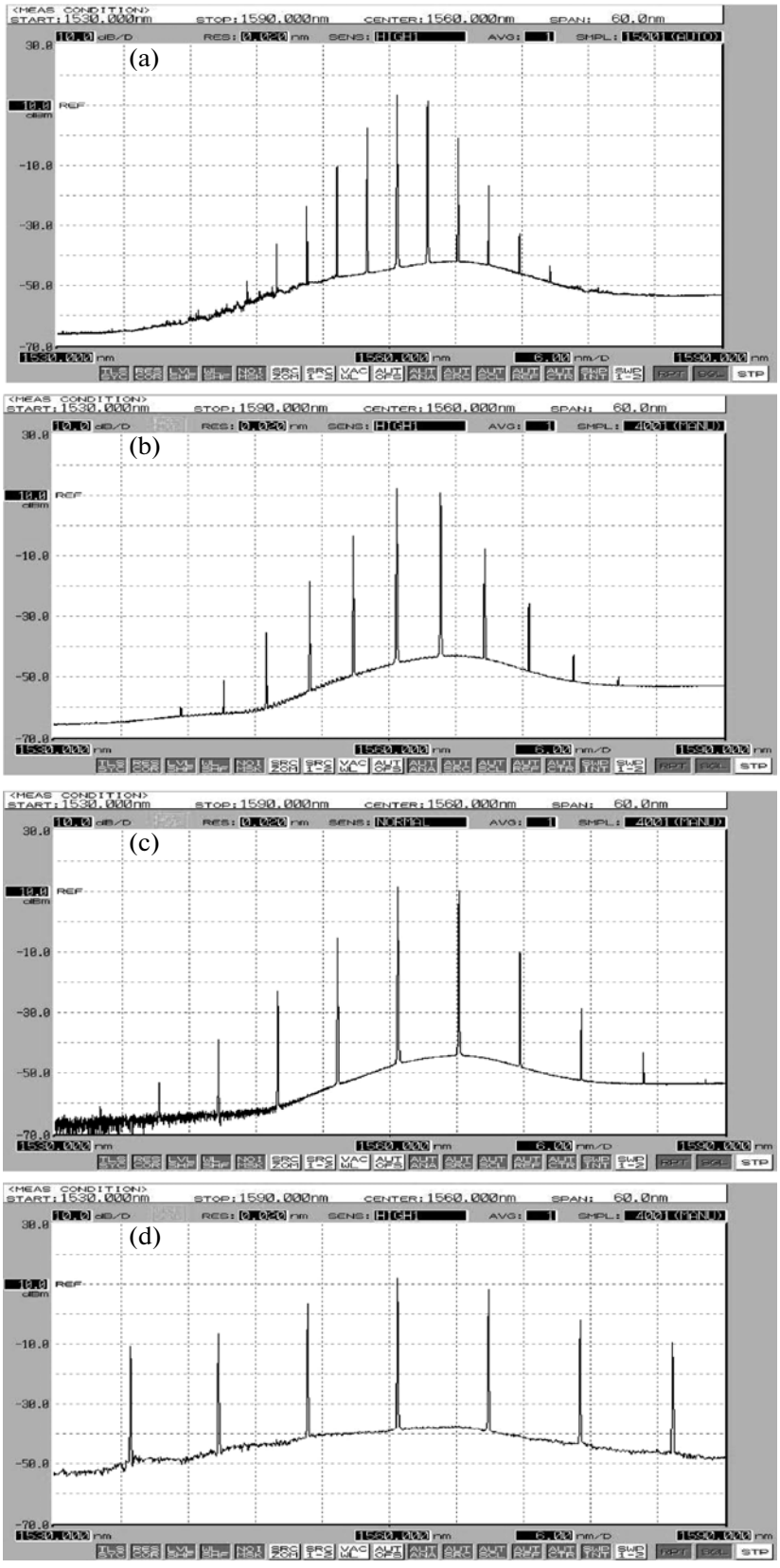

Fig. 4. Multiple wavelengths generated with continuously tunable wavelength spacing. The wavelength spacing is (a) 2.6, (b) ~4.0, (c) ~5.4, and (d) ~8.0 nm, respectively.

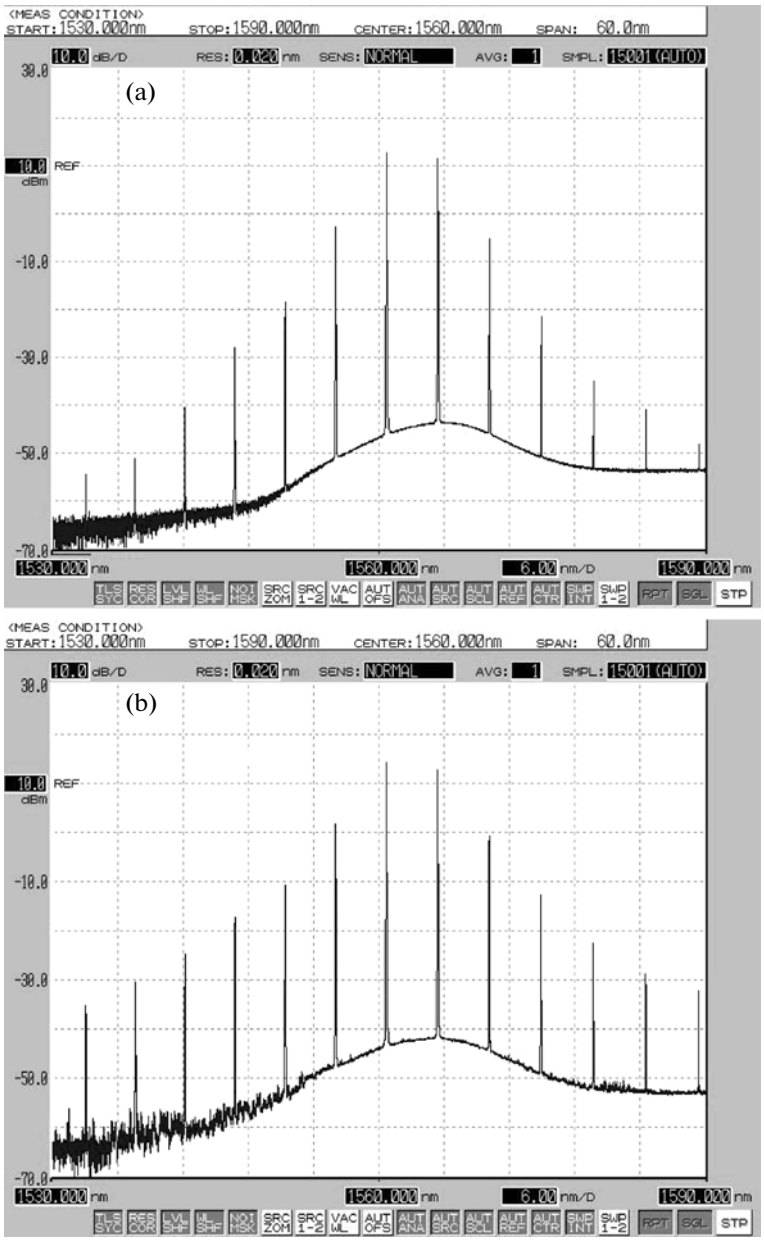

Fig. 5. Multiple-wavelength generation at different pump powers of MMLD. The pump power of MMLD is (a) 5 and (b) 6 W, respectively.

amplified by EDFAs and the multi-mode pumping light are coupled into the EYDF together through the (2 + l) × 1 MMC, and then the power of signal is boosted to watt level.

The isolators (ISOs) are utilized to prevent the amplified spontaneous emission (ASE) from reflecting to the gain medium. A variable optical attenuator (VOA) is used to protect the optical spectrum analyzer (OSA).

The two launched waves ω_1 and ω_2 are generated by their respective cavity with the same configuration but different FBG (FBG1 or FBG2) as shown in Fig. 2. A segment of EDF is pumped by a 980 nm single-mode laser diode (LD) through a wavelength-division multiplexer (WDM), and the laser is outputted through a 10/90 coupler. With different FBGs different wavelengths are generated, i.e., the incident wave ω_1 corresponding to the reflected center wavelength λ_1 is produced by FBG1 as shown in Fig. 2a, while ω_2 corresponding to λ_2 is produced by FBG2 as shown in Fig. 2b. When we stretch the grating by a pair of displacement platform slowly, the reflected center wavelength of FBG can continuously shift toward the longer wavelength. In our experiment, the wavelength

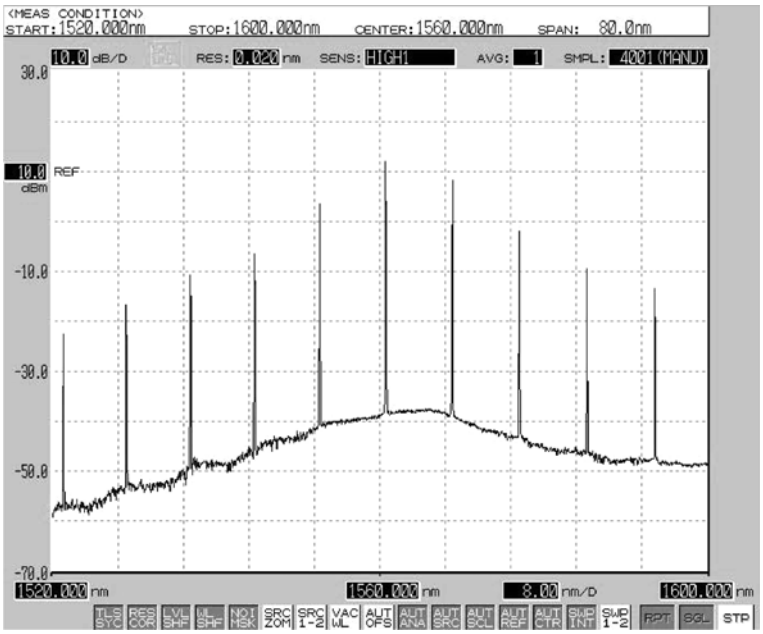

Fig. 6. Multiple wavelengths obtained at the pump power of ~7 W.

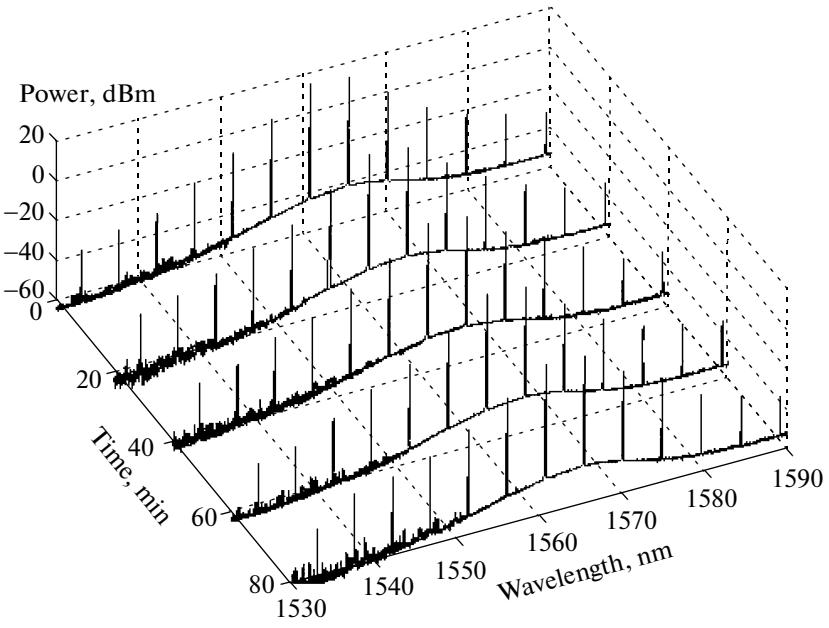

Fig. 7. Time stability of the proposed fiber laser at the time interval of 20 min.

spacing is changed mainly through stretching the FBG2.

It is well known that FWM in optical fibers refers to a nonlinear interaction among four different waves, which requires matching of the energy and wave-vector. The latter requirement is often considered as phase matching [18, 20]. In quantum-mechanical framework, FWM occurs when photons- from one or more waves are annihilated and new photons are created at different frequencies such that the net energy and momentum are conserved during the parametric interaction [24]. Generally, the degenerate FWM process easily takes place in optical fiber, which refers to two photons from the same pump wave (e.g., ω_p) are

absorbed and two new photons (e.g., ω_i and ω_s) are created (i.e., $2\omega_p = \omega_i + \omega_s$). The cascaded FWM process can be described briefly as following. A sample of the cascaded FWM is depicted in Fig. 3 to understand the process. The two incident waves ω_1 and ω_2 interact due to the degenerate FWM effect and the new waves ω_3 and ω_4 are generated (i.e., $\omega_3 = 2\omega_1 - \omega_2$ and $\omega_4 = 2\omega_2 - \omega_1$). Then the waves ω_3 and ω_1 carry out the degenerate FWM process and generate a new wave ω_5 (i.e., $\omega_5 = 2\omega_3 - \omega_1$). By the similar process the new wave $\omega_6 = 2\omega_4 - \omega_2$ is created. All the new waves are produced in this way, which is referred as cascaded FWM or multiple FWM [24–26]. Moreover, the multiple waves have the same separation of angular frequency $\Delta\omega$ (i.e., $\Delta\omega = |\omega_1 - \omega_2|$).

3. RESULTS AND DISCUSSIONS

In our experiments, the wavelength of two incident waves are λ_1 =1560.7 nm and λ_2 = 1563.3 nm, respectively. By injecting ω_1 and ω_2 into the PCF, multiple wavelengths are emitted simultaneously through the cascaded FWM process. The FBG2 is fixed on a pair of displacement platform. When we adjust the displacement platform slowly, FBG2 is stretched and λ_2 continuously shifts towards the longer wavelength. As a result, the spacing between λ_1 and λ_2 is increased. Successively, the multi-wavelength fiber laser with continuously tunable wavelength spacing can be achieved. Experimental results show that the wavelength spacing can be continuously tuned as shown in Fig. 4. Before stretching the FBG2, the wavelength spacing $\Delta\lambda$ is 2.6 nm as shown in Fig. 4a, and the pump power of MMLD is 4.5 W. When stretching the FBG2 slowly, the $\Delta\lambda$ is increasing continuously in a range from 2.6 nm to ~8 nm. The wavelength spacing as shown in Fig. 4b to Fig. 4d is ~4.0, ~5.4, and ~8.0 nm, and the corresponding pump power of MMLD is 4.5, 4.5, and 6.0 W, respectively. Multi-wavelength source with adjustable wavelength spacing can increase the operational flexibility and hence it can find more potential applications.

Figure 5 shows the generation of multiple wavelengths at different pump powers of MMLD. It demonstrates that the efficiency of cascaded FWM can be improved by increasing the pump power of MMLD. Figures 5a and 5b show the multi-wavelength generation at the pump power of 5 and 6 W, respectively. It can be seen that the optical signal-to-noise ratio (SMSR) of wavelengths is increased when the pump power of MMLD is enhanced. The total number of wavelength with a SMSR of >30 dB is 7 in Fig. 5a, while it increases to 8 in Fig. 5b. Note that the two launched wavelengths are λ_1 = 1560.7 nm and λ_2 = 1565.7 nm in Fig. 5. An excellent result is obtained at the pump power of MMLD of 7 W as shown in Fig. 6. In this case, the two launched wavelengths are λ_1 = 1560.7 nm and λ_2 = 1566.8 nm, respectively. It can be seen from Fig. 6 that as many as ten lasing lines with a high SMSR of >30 dB are generated.

The proposed multi-wave length fiber laser also exhibits an excellent stability at room temperature. As an example, Fig. 7 shows a total of five repeated measurements at an interval of 20 min. The two launched wavelengths are λ_1 = 1560.7 nm and λ_2 = 1565.7 nm, and the pump power of MMLD is 6 W. Measured result indicates that the peak power variation is less than 0.5 dB.

4. CONCLUSIONS

In this paper, we have demonstrated a multi-wavelength laser based on the cascaded FWM in highly-nonlinear PCF. The multi-mode pumping erbium/ytterbium co-doped double-cladding fiber amplification technique is employed for boosting the power of the two pump waves. A piece of highly-nonlinear near-zero-dispersion-flattened PCF offers an opportunity for generating highly efficient cascaded FWM. The spacing of generated multiple wavelengths can be continuously tuned by stretching the FBG2. Experimental results show that multiple wavelengths with a high optical SMSR of >30 dB are generated. Moreover, the proposed fiber laser with multi-wavelengths lasing simultaneously can work stably at room temperature.

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